



US007085451B2

(12) **United States Patent**
Gaylord et al.

(10) **Patent No.:** **US 7,085,451 B2**

(45) **Date of Patent:** **Aug. 1, 2006**

(54) **OPTICAL FIBER GRATINGS WITH
 AZIMUTHAL REFRACTIVE INDEX
 PERTURBATION**

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(*) Notice: Subject to any disclaimer, the term of this
 patent is extended or adjusted under 35
 U.S.C. 154(b) by 46 days.

(21) Appl. No.: **11/220,337**

(22) Filed: **Sep. 6, 2005**

(65) **Prior Publication Data**

US 2006/0008208 A1 Jan. 12, 2006

Related U.S. Application Data

(62) Division of application No. 09/860,790, filed on May
 18, 2001, now Pat. No. 6,832,023.

(60) Provisional application No. 60/205,990, filed on May
 19, 2000.

(51) **Int. Cl.**
G02B 6/34 (2006.01)
G02B 6/02 (2006.01)

(52) **U.S. Cl.** **385/37; 385/123; 385/124**

(58) **Field of Classification Search** None
 See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,982,916 A * 9/1976 Miller 65/420
 6,768,851 B1 * 7/2004 Chiang et al. 385/124
 6,778,747 B1 * 8/2004 Bhagavatula et al. 385/123

* cited by examiner

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 Horstemeyer & Risley

(57) **ABSTRACT**

The present invention relates to a type of optical fiber grating having an azimuthal refractive-index perturbation. The optical fiber includes a fiber grating that has a plurality of grating elements formed therein. At least one of the grating elements has a spatially varying index of refraction that varies azimuthally about the centerline of the optical fiber. The fiber grating acts as a band-stop optical spectral filter. In addition, since fiber-cladding modes are weakly-guided modes, their power can be easily dissipated by scattering, bending, stretching, and/or rotating the optical fiber. Multiple configurations of these gratings within an optical fiber are given. Methodologies are given for the fabrication of these gratings. Devices are presented which can dynamically attenuate, tune, switch, or modulate the wavelength spectral characteristics of an optical signal.

17 Claims, 12 Drawing Sheets

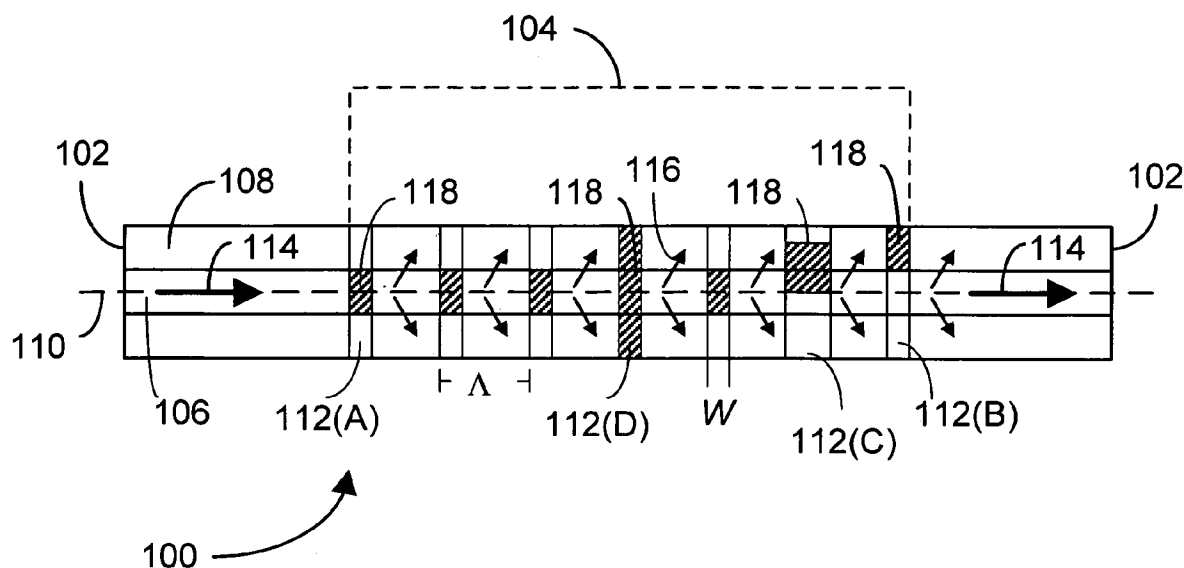


FIG. 1C

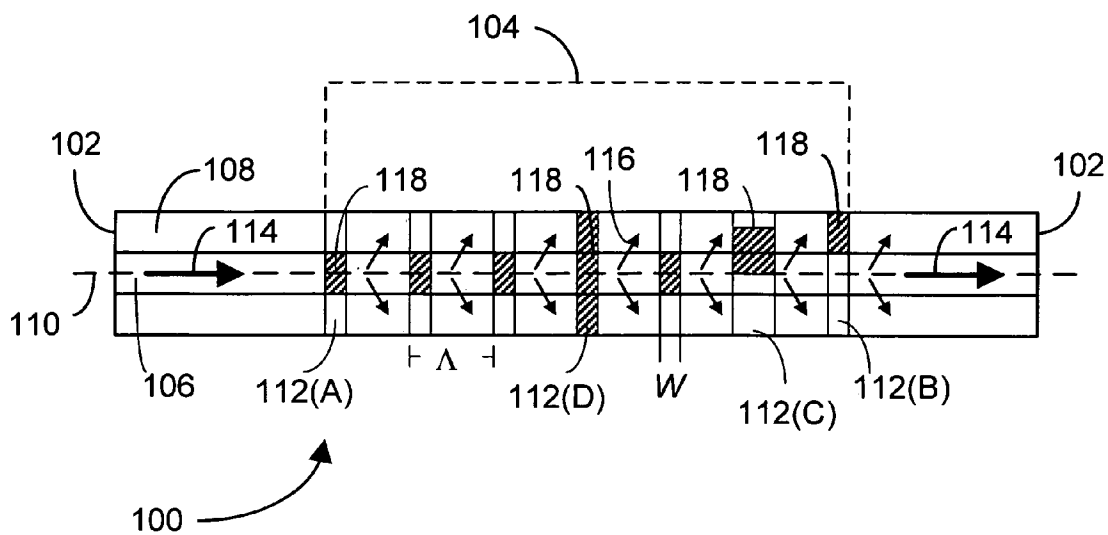


FIG. 2

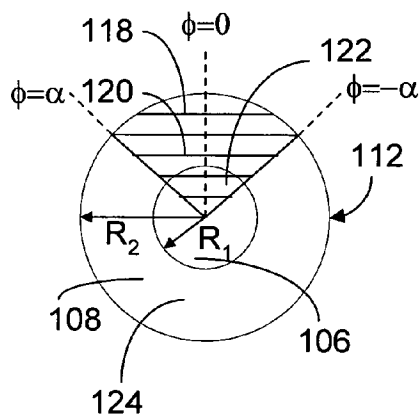


FIG. 3

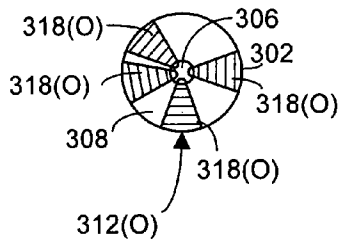


FIG. 4 O

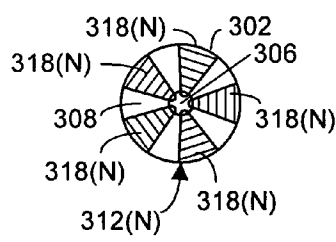


FIG. 4 N

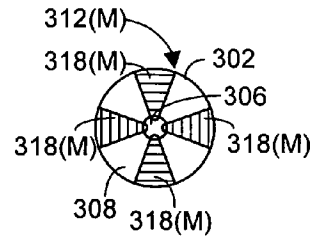


FIG. 4 M

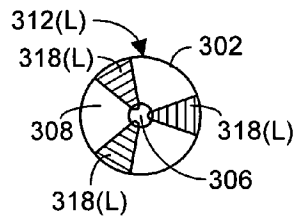


FIG. 4 L

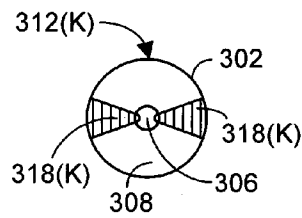


FIG. 4 K

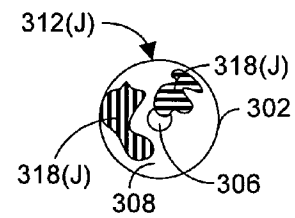


FIG. 4 J

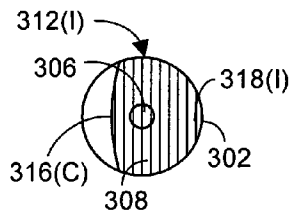


FIG. 4 I

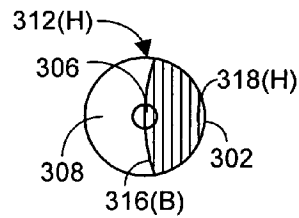


FIG. 4 H

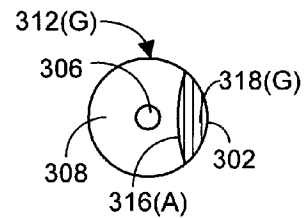


FIG. 4 G

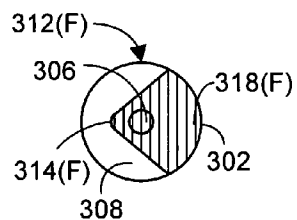


FIG. 4 F

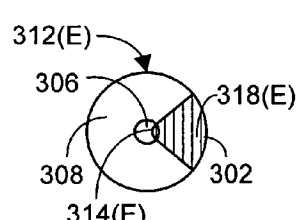


FIG. 4 E

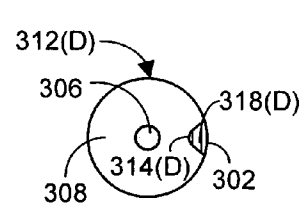


FIG. 4 D

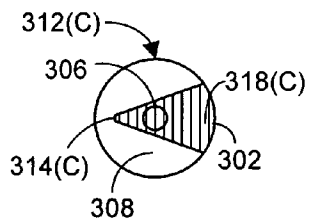


FIG. 4 C

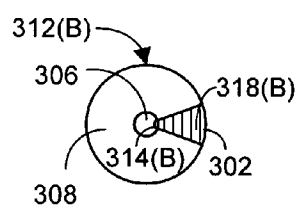


FIG. 4 B

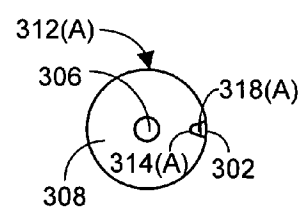


FIG. 4 A

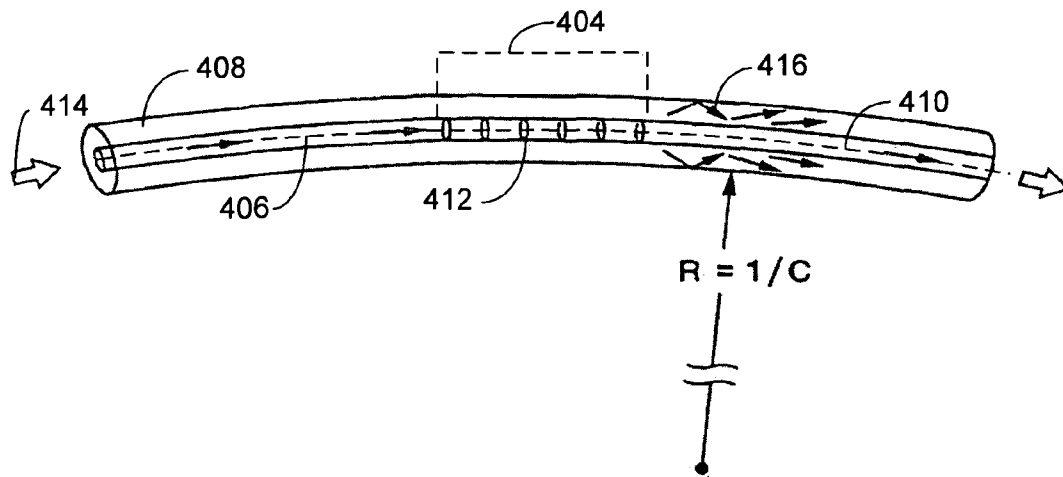


FIG. 5

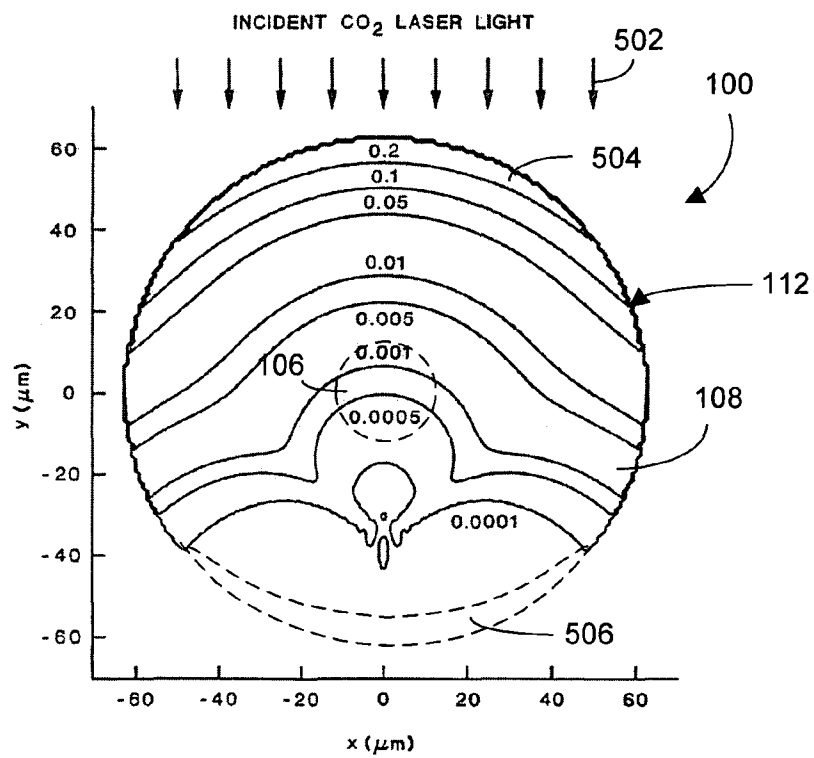


FIG. 6

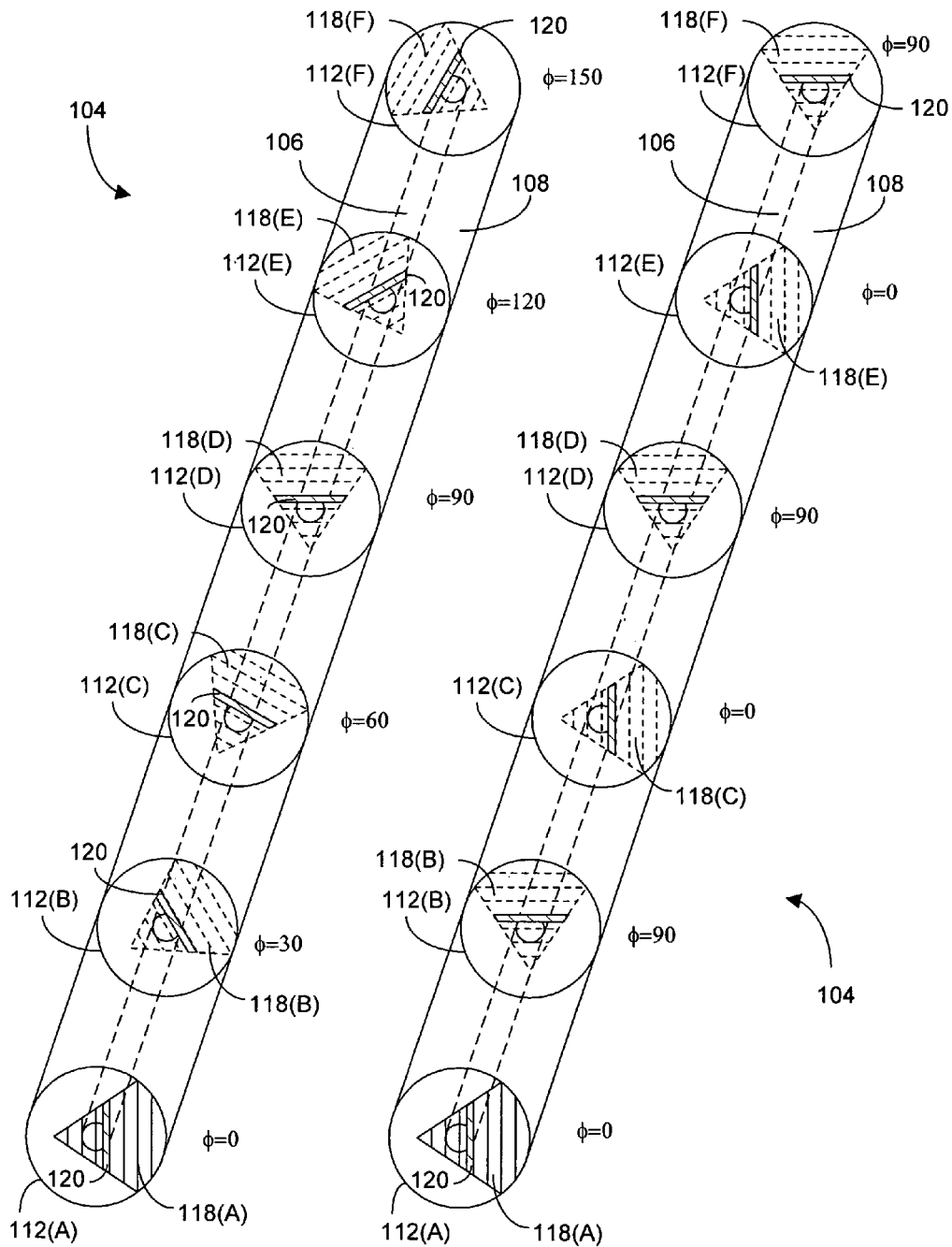


FIG. 7A

FIG. 7B

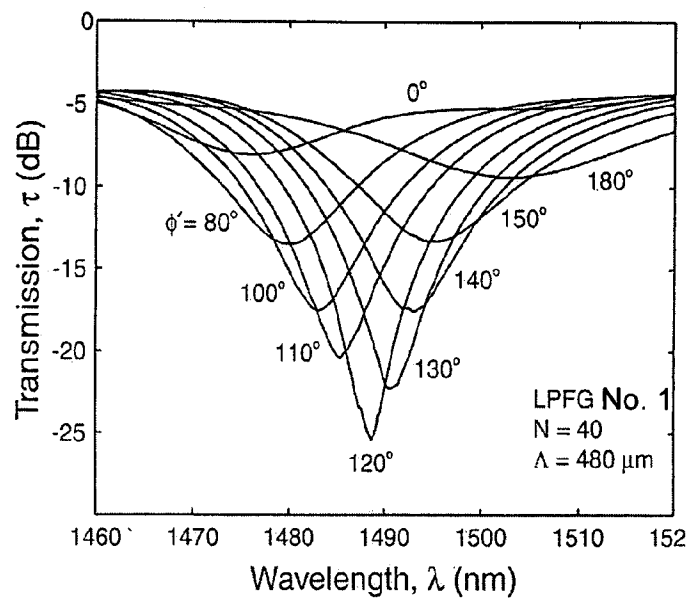


FIG. 8

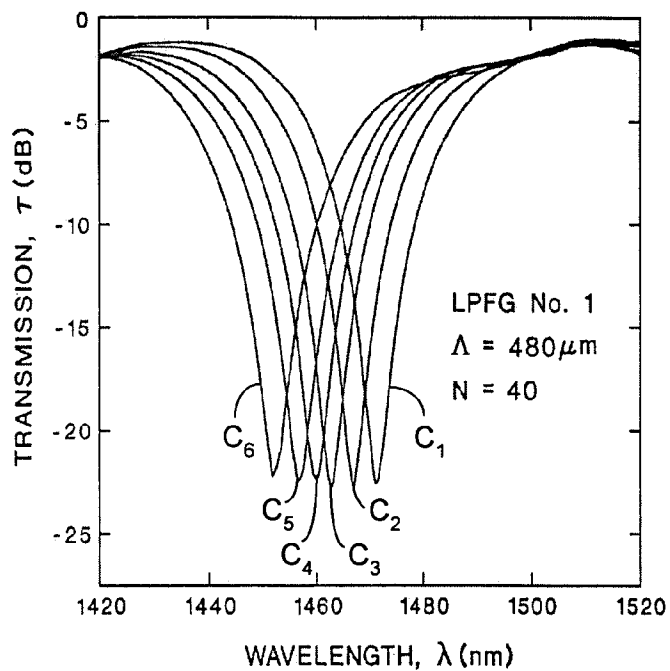


FIG. 9

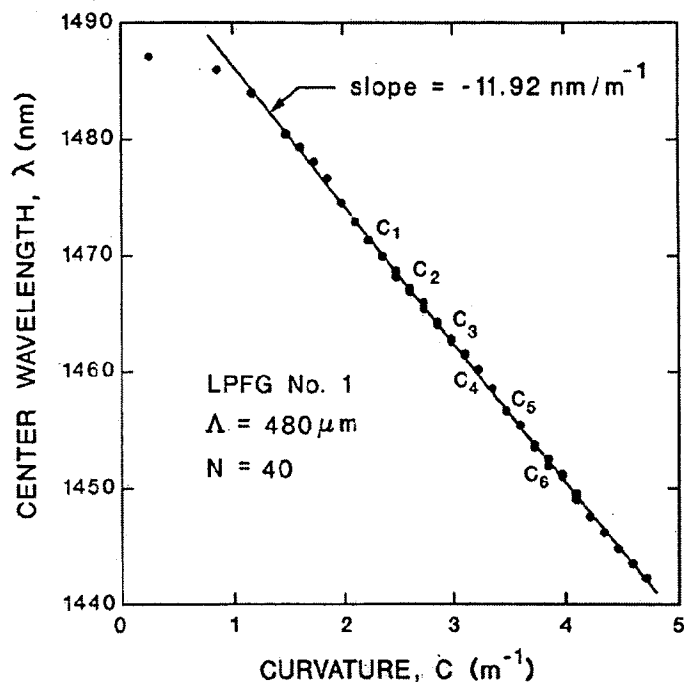


FIG. 10

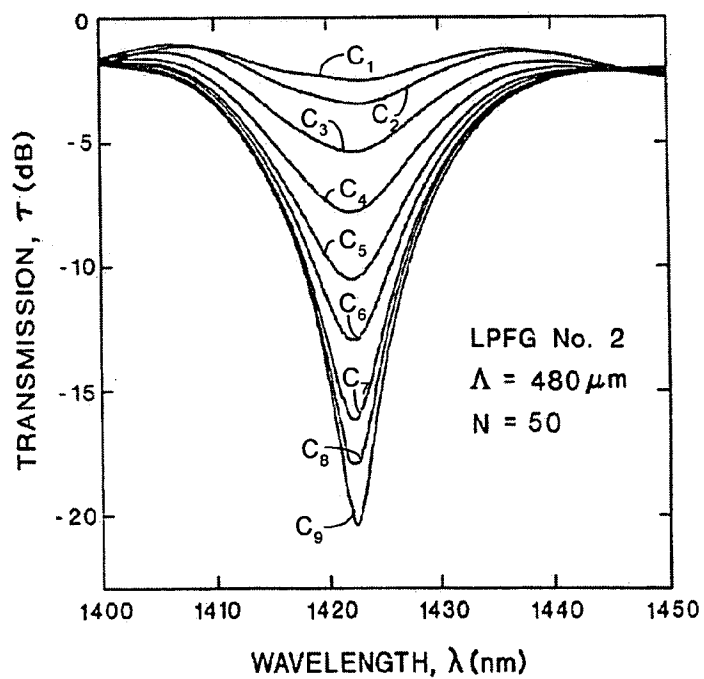


FIG. 11

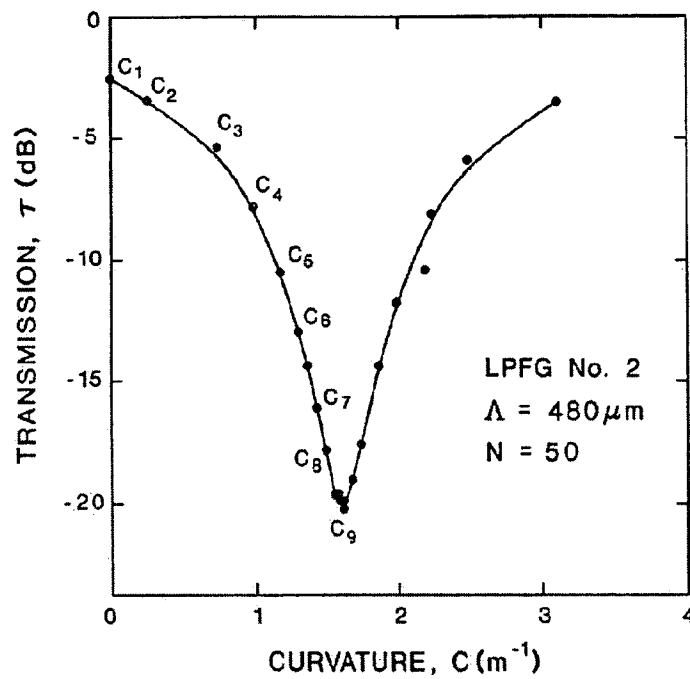


FIG. 12

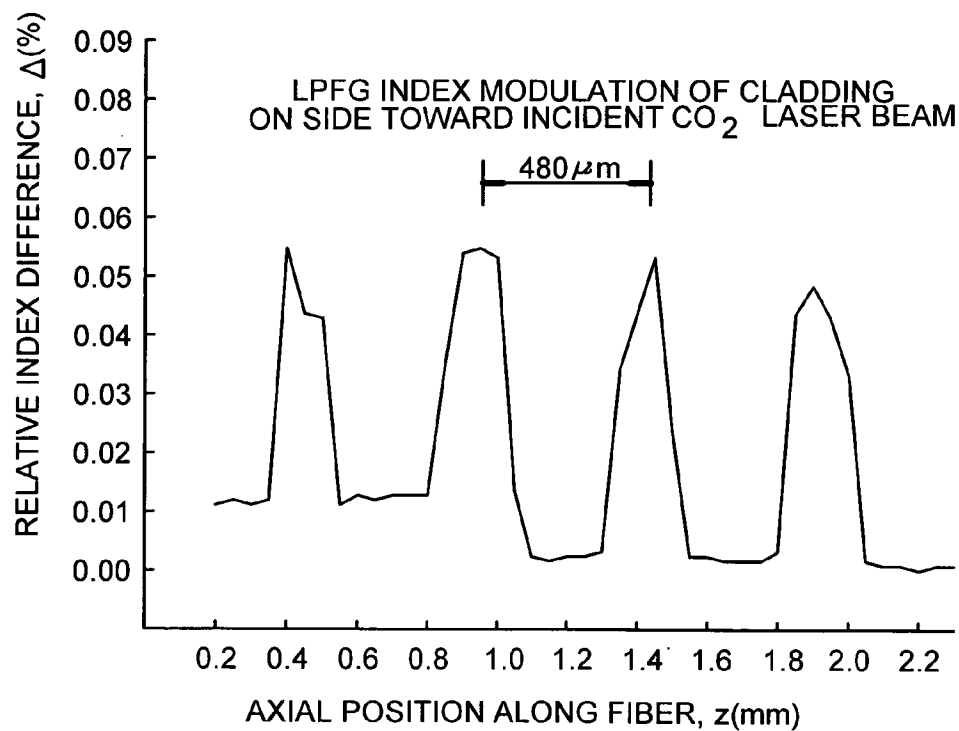
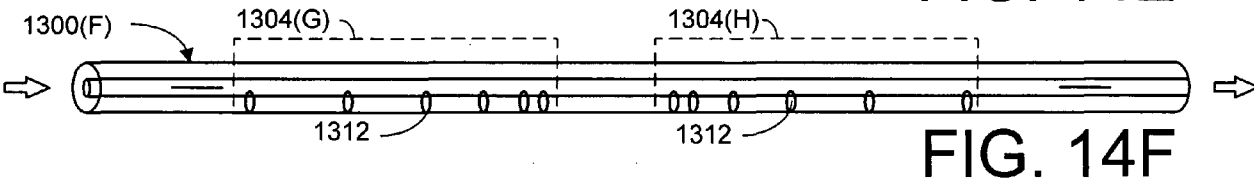
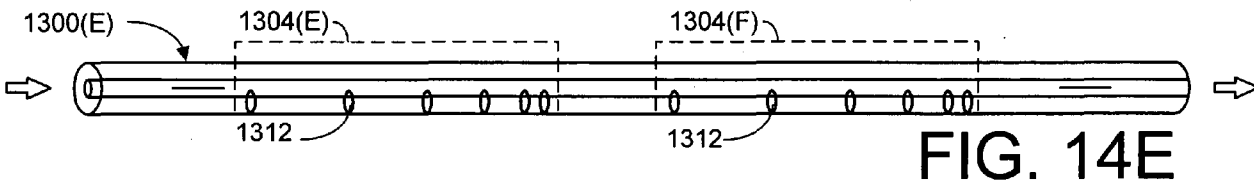
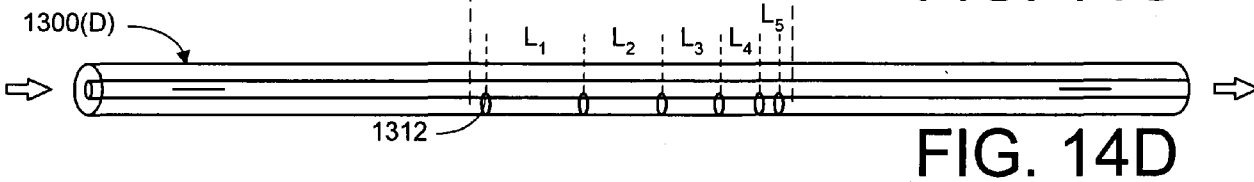
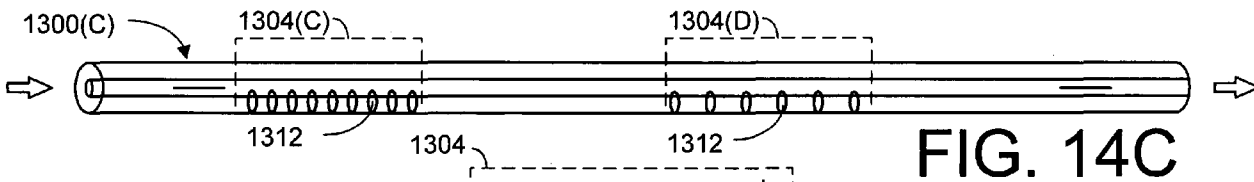
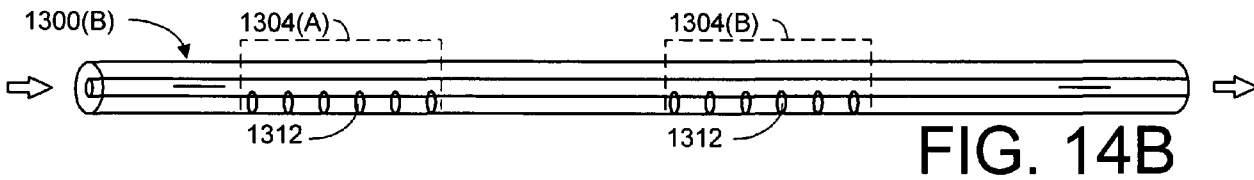
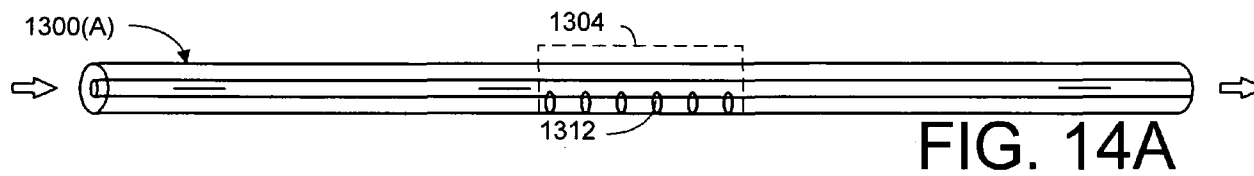
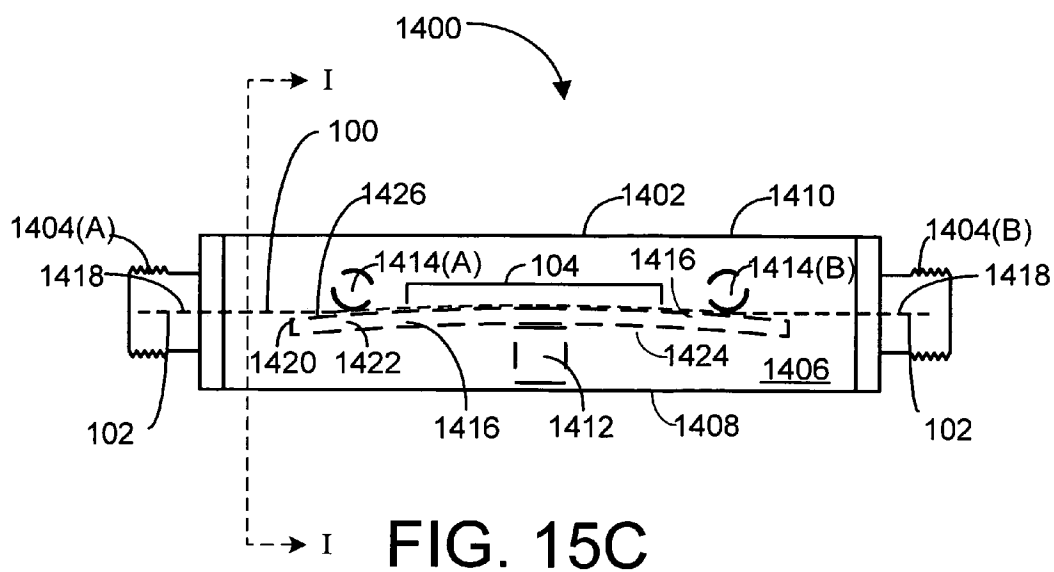
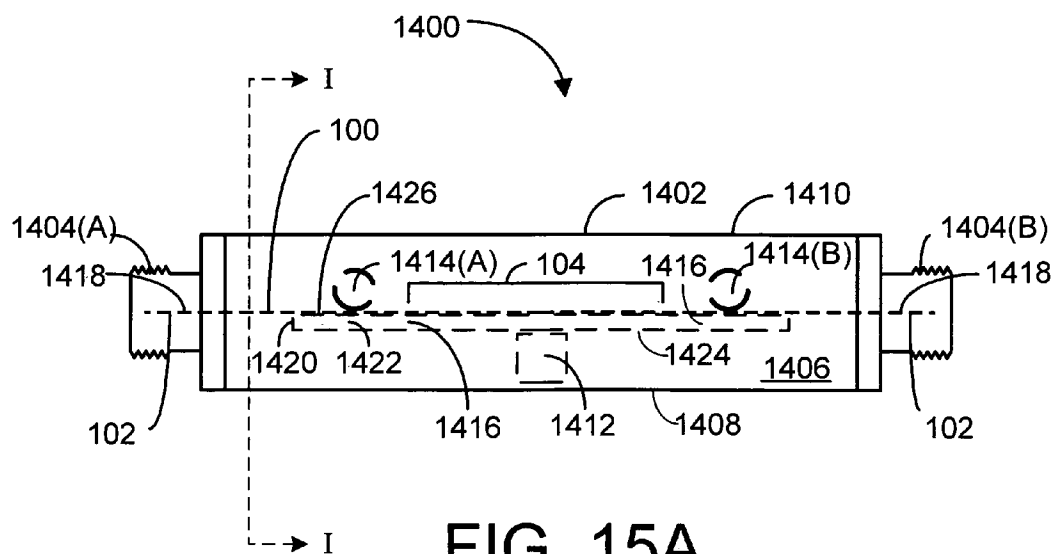


FIG.13





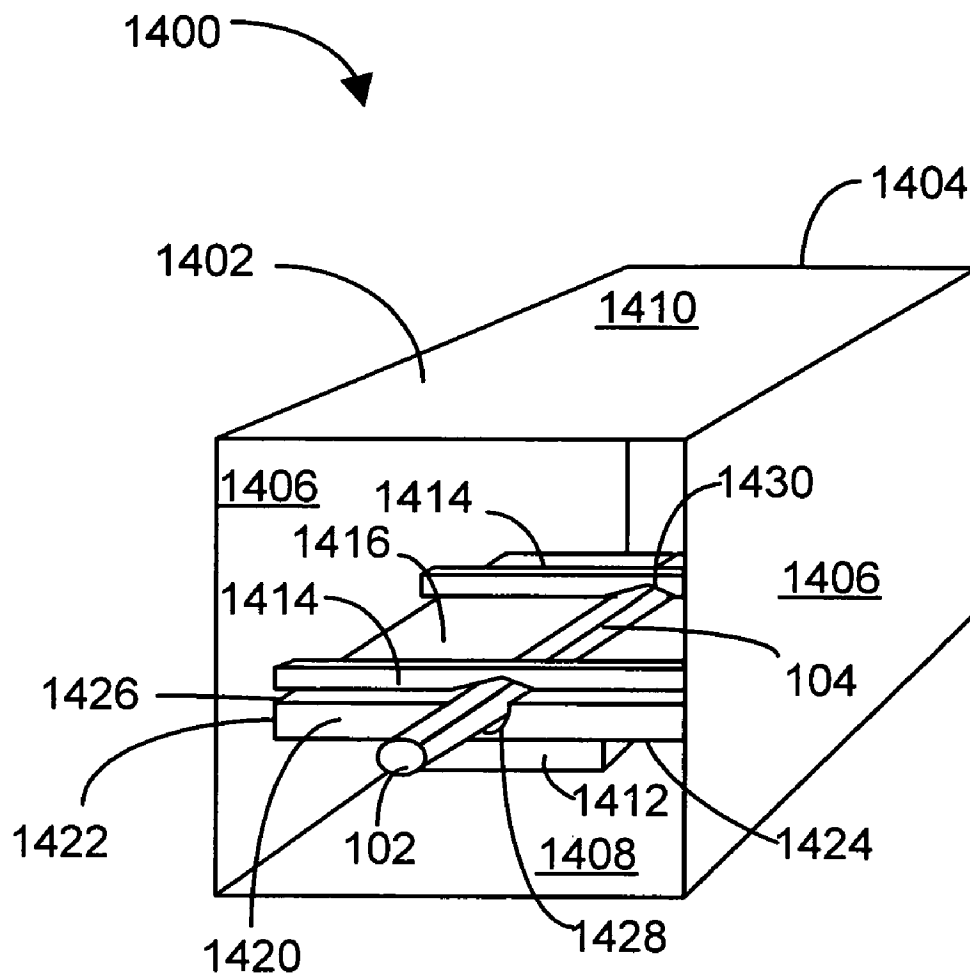


FIG. 15B

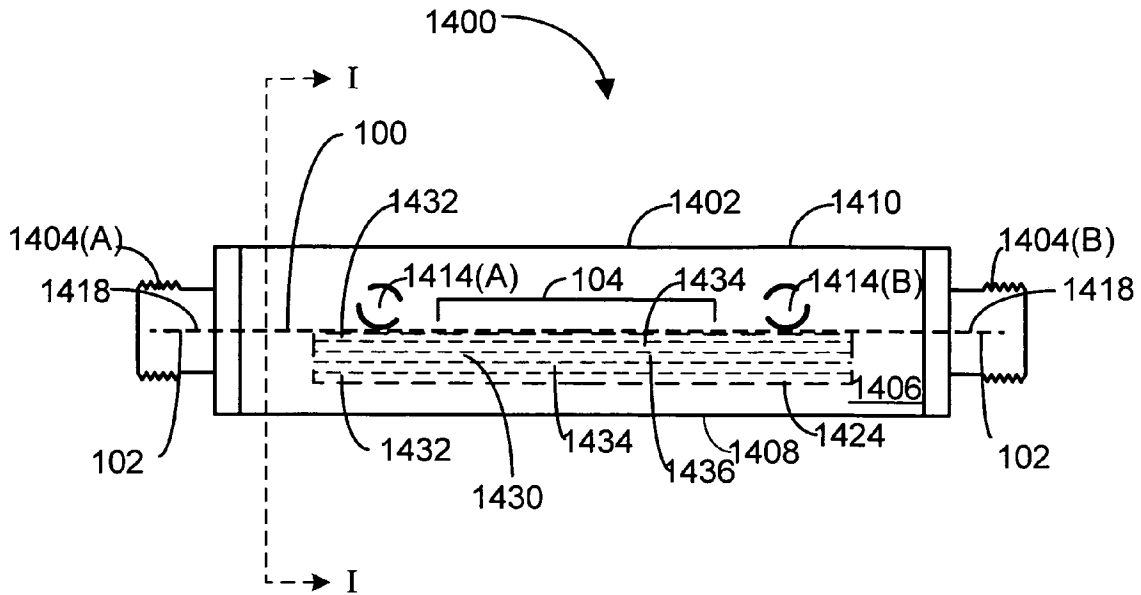


FIG. 15D

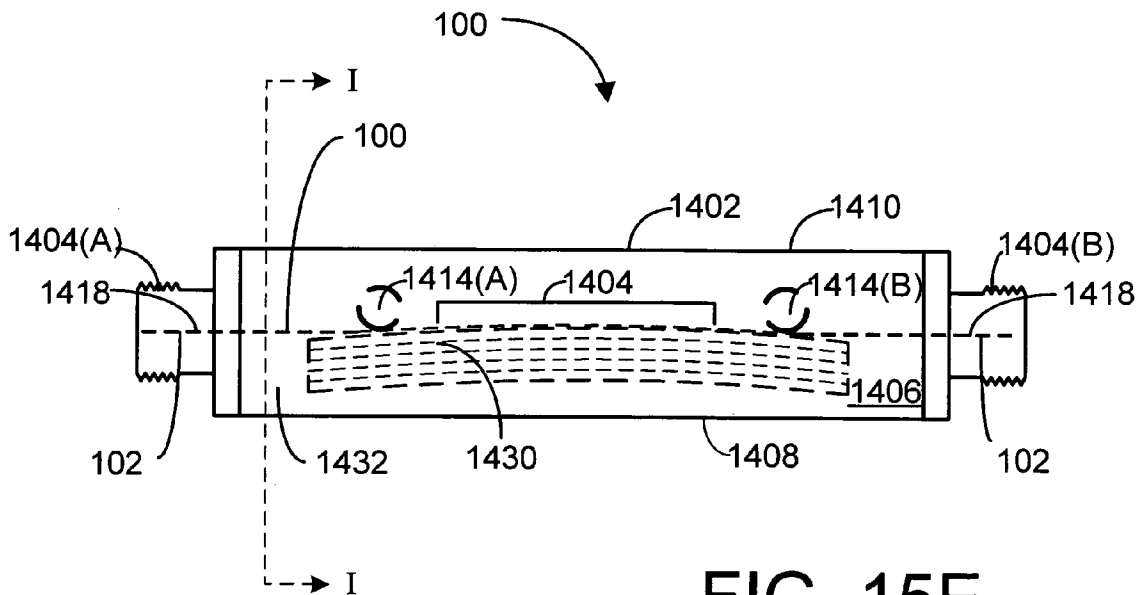


FIG. 15E

1

OPTICAL FIBER GRATINGS WITH AZIMUTHAL REFRACTIVE INDEX PERTURBATION

CROSS-REFERENCE TO RELATED APPLICATION

This application is a divisional of U.S. utility application entitled, "Optical Fiber Gratings with Azimuthal Refractive Index Perturbation, Method of Fabrication, and Devices for Tuning, Attenuating, Switching, and Modulating Optical Signals," having Ser. No. 09/860,790, filed May 18, 2001, U.S. Pat. No. 6,832,023, which is entirely incorporated herein by reference and which claims priority to copending U.S. provisional application entitled, "Long Period Fiber Grating Wavelength Tuners/Modulators/Switches," having Ser. No. 60/205,990, filed May 19, 2000, which is entirely incorporated herein by reference. This application is related to copending U.S. utility application entitled "Optical Fiber Gratings with Azimuthal Refractive Index Perturbation, Method of Fabrication, and Devices for Tuning, Attenuating, Switching, and Modulating Optical Signals," having Ser. No. 10/886,800, filed Jul. 8, 2004, which is entirely incorporated herein by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

The U.S. government may have a paid-up license in this invention and the right in limited circumstances to require the patent owner to license others on reasonable terms as provided for by the terms of grant no. EEC-94-02723 awarded by the National Science Foundation.

FIELD OF THE INVENTION

The present invention is directed, in general, to optical fiber gratings, to their fabrication, and to their use as devices in optical systems.

BACKGROUND OF THE INVENTION

Optical gratings are useful in controlling the paths of propagating light, particularly light composed of multiple wavelengths. Optical gratings are useful in manipulating the transmittance and/or the propagation direction of particular wavelengths within an optical signal. Since optical signals propagate inside optical waveguides, an optical grating consists of a periodic perturbation (variation) of an optical-waveguide parameter such as the real and/or imaginary part of its refractive index or its thickness. One of the most important types of optical waveguides is the optical fiber. Basically, optical fibers are thin strands of glass capable of transmitting information-containing optical signals over long distances with very low loss. In essence, an optical fiber is a small diameter waveguide comprising a core having a first index of refraction surrounded by a cladding having a second (lower) index of refraction. Provided the refractive index of the core exceeds that of the cladding, a light beam propagated within the core may exhibit total internal reflection, and is guided along the length of the core. Typical optical fibers are made of high purity silica with various concentrations of dopants added to control the index of refraction. Optical fibers that have gratings, perturbations in the refractive index, are of particular interest as components in modern multi-wavelength communication systems, such as wavelength-division-multiplexed optical communication systems.

2

In-fiber optical gratings are important elements for selectively controlling specific wavelengths of light transmitted within optical systems such as wavelength-division-multiplexed optical communication systems. Such gratings may include short-period fiber Bragg gratings and long-period fiber gratings. These gratings typically comprise a body of material with a plurality of spaced-apart optical grating elements disposed in the material. Often, the grating elements comprise substantially equally-spaced refractive index or optical absorption perturbations. For all types of gratings, it would be highly useful to be able to reconfigure the grating to adjust selectively the controlled wavelengths.

A cladding mode is a mode of light that is not confined to the core, but rather, is confined by the entire waveguide structure. Long-period fiber grating devices selectively forward-diffract light at specific wavelengths by providing coupling between core modes and cladding modes. In general, short-period fiber Bragg gratings can also diffract light into cladding modes. In this case, the cladding modes are back-diffracted. The period, Λ , of the perturbations is chosen to shift transmitted light in the region of a selected peak wavelength, λ_p , from a core guided mode into a cladding mode, thereby reducing in intensity a band of light having wavelengths centered about the peak wavelength λ_p . In other words, the fiber grating acts as a band-stop optical spectral filter. In addition, since fiber cladding-modes are weakly-guided modes, their power can be easily dissipated by scattering, bending, stretching, and/or rotating the optical fiber. Such devices are particularly useful for equalizing amplifier gains across a band of wavelengths used in optical communications systems.

Typically, the spacing between the periodic perturbations in a long-period grating is large compared to the freespace wavelength λ of the transmitted light. In contrast with conventional short-period fiber Bragg gratings, long-period gratings use a periodic spacing Λ that is typically about a hundred times larger than the transmitted freespace wavelength. In some applications, such as chirped gratings, the spacing Λ can vary along the length of the grating.

A difficulty with conventional short-period fiber gratings and long-period fiber gratings, however, is their inability to change (tune) dynamically their spectral characteristics. Each short-period fiber grating and each long-period grating with a given periodicity (Λ) selectively filters light with an unchanging attenuation and in an unchanging narrow bandwidth centered around the peak wavelength of coupling, λ_p . This wavelength is determined by $\lambda_p = (N_{core} \pm N_{cladding}) \Lambda$, where N_{core} and $N_{cladding}$ are the guided-mode effective indices of the core and the cladding modes, respectively. The "+" sign is valid for the case of backward-diffracted light by short-period gratings and the "-" sign is valid for forward-diffracted light by long-period gratings. The value of N_{core} and $N_{cladding}$ depend on the wavelength, on the core, cladding, and surrounding medium refractive indices, and on the core and cladding radii.

Various techniques have been developed to extract light from the core of an optical fiber so that the light may be modulated or filtered. In one approach, part of the cladding surrounding the core of the optical fiber is polished away on one side of the fiber so that a portion of the light in the core can be coupled into the cladding. In another approach, disclosed in U.S. Pat. No. 6,058,226, which is hereby incorporated by reference, a voltage is applied to an electrically sensitive material coupled to the exterior of an optical fiber. The applied voltage is used for modulating the light being transmitted through the optical fiber. In yet still another approach, disclosed in U.S. Pat. No. 6,055,348,

which is hereby incorporated by reference, a longitudinal strain is applied to a fiber grating so that the spacing between the grating elements are changed to shift the wavelength response of the device to provide a tunable optical grating device.

Multi-wavelength communication systems require continuous adjustment of the signal levels. If the signal adjustment is wavelength independent then these devices are called variable optical attenuators (VOA), while for the case of wavelength dependent attenuation they are called variable gain flattening filters. As a first example, in pre-emphasis filtering, some wavelength channels need to be equalized in intensity before they are combined in the fiber. As a second example, the reconfiguration and reallocation of wavelengths among the various nodes of a network by add/drop filtering requires these wavelength channels to be balanced in intensity with the optical network. As a third example, the gain of optical amplifiers, such as erbium-doped optical amplifiers, needs to be the same for all wavelengths, thus requiring wavelength-by-wavelength control of the optical gain. Optical amplifiers have deleterious peaks in their gain spectra that need to be flattened. As a fourth example, an adjustable wavelength and attenuation filter is needed for suppressing amplifier spontaneous emission (ASE) in optical amplifiers. As a fifth example, in a related application, there is a need to control the output power of tunable lasers to be constant over multiple wavelength ranges in order to provide a constant output power over any selected wavelength range.

Multi-wavelength communication systems also require network control functions to be available. As a first example, each wavelength channel should be tagged or labeled. This can be accomplished by modulating each channel wavelength with a slightly different kilohertz frequency. As a second example, network supervisory information needs to be distributed within the existing optical network (without resorting to external wire-based communications) and without affecting any of the data channels within the optical network. This can be done by modulating the existing data channels at kilohertz frequencies with the supervisory information to be distributed.

All of the above needs require a device whose transmission can be controlled in wavelength and amplitude. Adjusting the fiber grating as described in this invention allows tuning of the center wavelength or the adjustment of the attenuation at a fixed wavelength or a combination of these. As such, an adjustable fiber grating is capable of fulfilling all of the above listed application needs. Generally, prior art optical fiber gratings have grating elements that are typically disposed in the optical fiber core and perpendicular to the longitudinal centerline of the optical fiber. However, there are also optical fiber gratings that have grating elements that are slanted, instead of perpendicular, with respect to the centerline of the optical fiber. Several patents also exemplify fiber gratings with slanted refractive-index variation, which are U.S. Pat. No. 5,430,817 to A. M. Vengsarkar, U.S. Pat. No. 5,764,829 to J. Boyd et al. It is accordingly an object of the present invention to provide a new class of fiber gratings.

SUMMARY OF THE INVENTION

The present invention provides an apparatus and method for tuning, attenuating, switching, and modulating optical signals in a waveguide.

Briefly described, in architecture, one embodiment of the apparatus, among others, can be implemented as follows. A length of optical comprising a core region with a refractive

index distribution and a cladding region with a refractive index distribution, the cladding region disposed on the core region. The optical fiber includes an azimuthally varying grating element. The optical properties of the optical fiber are changed by physical manipulation of the optical fiber.

The present invention can also be viewed as providing methods for selecting the coupling between modes in an optical fiber. In this regard, one embodiment of such a method, among others, can be broadly summarized by the following steps: an optical fiber having a grating region, which includes at least one azimuthally varying grating element, is disposed in an optical network; and the optical fiber is oriented in a predetermined position. The coupling between optical modes in the optical fiber are related to the positioning of the optical fiber.

The present invention can also be viewed as providing methods for making grating elements that have azimuthal variation in an optical fiber. In this regard, one embodiment of such a method, among others, can be broadly summarized by the following steps: disposing a length of optical fiber in a predetermined position; and heating a portion of the optical fiber. The heating of the optical fiber produces a perturbation in the refractive index of the heated portion of the optical. An alternative embodiment for making a grating element having an azimuthal variation can be broadly summarized by the following steps: disposing a dopant in a non-uniform pattern in an optical fiber; and irradiating the dopant with a laser beam. The irradiation by the laser beam of the dopant in the optical fiber produces a perturbation in the refractive index in the portion of the optical fiber having the dopant disposed therein.

Other systems, methods, features, and advantages of the present invention will be or become apparent to one with skill in the art upon examination of the following drawings and detailed description. It is intended that all such additional systems, methods, features, and advantages be included within this description, be within the scope of the present invention, and be protected by the accompanying claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale, emphasis instead being placed upon clearly illustrating the principles of the present invention. Moreover, in the drawings, like reference numerals designate corresponding parts throughout the several views.

FIG. 1A shows a schematic illustration of a fiber grating having slanted refractive index variation in the form of a slanted-fringe grating.

FIG. 1B and FIG. 1C show two ways to fabricate fiber gratings.

FIG. 2 shows a schematic view of an optical fiber having a grating region disposed there.

FIG. 3 is a cross sectional view of a grating element.

FIGS. 4A–4O are cross sectional views of exemplary grating elements.

FIG. 5 shows a bent optical fiber having a grating region disposed therein.

FIG. 6 shows a cross sectional view of normalized intensity of a transversely applied beam in an optical fiber.

FIGS. 7A and 7B show exemplary grating element configurations.

5

FIG. 8 shows rotational dependence of the transmission characteristics of a grating region that includes grating elements, which were written into the optical fiber by a CO₂ laser beam.

FIG. 9 shows transmission spectral characteristics with bending curvature as a parameter for a glass optical fiber having a grating region that includes grating elements, which were written into the optical fiber by a CO₂ laser beam.

FIG. 10 shows the center wavelength as a function of bending curvature for a glass optical fiber having a grating region that includes grating elements, which were written into the optical fiber by a CO₂ laser beam.

FIG. 11 shows transmission spectral characteristics with bending curvature as a parameter for a glass optical fiber having a grating region that includes grating elements, which were written into the optical fiber by a CO₂ laser beam.

FIG. 12 shows the transmission spectral characteristics as a function of bending curvature for a glass optical fiber having a grating region that includes grating elements, which were written into the optical fiber by a CO₂ laser beam.

FIG. 13 shows longitudinal relative index difference in an optical fiber.

FIGS. 14A–14F show exemplary configurations of fiber gratings in optical fibers.

FIGS. 15A–15C show an exemplary device for configuring an optical fiber.

FIGS. 15D and 15E show another exemplary device for configuring an optical fiber.

DETAILED DESCRIPTION

The present invention is directed to an improved type of fiber grating possessing a general azimuthal refractive index variation, as well as a fabrication method, and optical devices for adjusting the optical characteristics of the grating. The optical adjustment device provides a means for tuning, attenuating, switching, and modulating optical signals in the waveguide. For the purposes of this disclosure, a preferred embodiment is discussed with the optical adjustment device disposed in an optical fiber containing a long-period fiber grating (LPFG). It is to be understood that the invention includes, but is not limited to, in-fiber gratings, such as LPFGs and short-period fiber Bragg gratings.

In FIG. 1A, the grating has a refractive index variation 10, which varies from the refractive index of the core, inside the core 11 of a single-mode fiber 15. In the preferred embodiment, the refractive index variations 10 have a periodicity of Λ and form an angle θ 13 with respect to the longitudinal fiber axis 25. This type of structure is called a “slanted” grating. In a conventional optical fiber grating, the refractive index variation 10 is uniform within the slanted grating and within “unslanted” gratings, i.e., gratings that are perpendicular with respect to the centerline. In other words, the variation of the refractive index of the core is uniform for all values of Ψ angular rotations about centerline 25 in the plane of the refractive index variation 10. In the preferred embodiment, the refractive index variation 10 is rotationally non-uniform in the plane defining the refractive index variation. For the purposes of this disclosure azimuthal angles and rotations are measured in the plane defined by the refractive index variation. In the embodiment illustrated in FIG. 1A, there is no index perturbation in the fiber cladding-region 12. A method of developing these gratings is via direct illumination of the fiber by a UV excimer laser. In

6

FIG. 1B, the fiber 15 comprised by the cladding region 12 and the core region 11 is illuminated by the laser beam 22. The amplitude mask 20 controls the shape of the laser beam incident upon the fiber. The laser is turned on and laser-light passes through the slit 21 and impinges on the fiber. After the laser is turned off, the fiber 15 is then translated by distance Λ and then the laser is turned on again. The same process is repeated many times such that the formed grating has the desired number of periods Λ . In an alternative approach shown in FIG. 1C, the amplitude mask 23 has several thin slits and an interference intensity pattern impinges the fiber. This method can be used for the development of short-period fiber Bragg gratings.

Referring to FIG. 2, the optical fiber 100 is a conventional single-mode optical fiber used in transmitting light signals in a network, such as a telecommunications network. Light is transmitted through the optical fiber 100 in a guided mode through the core 106, the core having a refractive index, n_{core} , greater than the refractive index, n_{cladding} , of the cladding 108. Although, the core 106 has been illustrated as a single region having symmetry about the centerline 110, those skilled in the art are familiar with cores that have a plurality of concentric annular regions disposed therein, non-limiting examples of which are dispersion shifted optical fibers. The scope of the invention includes cores that have a generally uniform index of refraction and cores that have a plurality of regions with differing indices of refraction.

In one embodiment, the optical fiber 100 is a glass optical fiber. Those skilled in the art recognize that there are many glass optical fibers such as fluoride glass, doped glasses, and co-doped glasses. Examples of dopants used in glass optical fibers include, but are not limited to, germanium, boron, and hydrogen. Furthermore, optical fibers are also made from plastic materials and/or polymer materials, and are also included within the scope of the invention. Most, if not all, optical fibers having cores and/or claddings in which the magnitude of the refractive index of the core/claddings can be irreversibly or reversibly changed are intended to be included within the scope of the present invention.

Referring to FIG. 2, the optical fiber 100 includes one or more fiber gratings 104, each comprising a plurality of grating elements 112 of width W . For the purposes of this disclosure, a grating element 112 is generally a planar portion of width W of the optical fiber 100. The grating element 112 includes a perturbation 118 in the index of refraction of the optical fiber. The perturbation 118 can be in the index of refraction of the core 106, as shown for grating element 112(A), or in the cladding 108, as shown for the grating element 112(B), or the perturbation can extend from the core 106 into the cladding 108, as shown for the grating element 112(C), or the perturbation can extend across the width of the optical fiber 100, as shown for the grating element 112(D). Although the grating elements 112 are generally shown as being of uniform width, it should be noted that this is for illustrative purposes only and that the width of each perturbation can vary. For example, the grating element 112(C) is illustrated as having a width that is twice the width of grating element 112(A). In addition, the width of the perturbation can be non-uniform, for example, wide at one place and narrow in another part of the grating element. The width of the grating element is such that two generally parallel planes separated by a width W surround the perturbation.

It should also be noted that although the grating elements 112 are illustrated as being generally parallel to each other and generally perpendicular to centerline 110 that this con-

figuration is for illustrative purposes. In an alternative embodiment, the grating elements **112** are obliquely aligned with respect to the centerline **110**. In yet another embodiment, the grating elements are obliquely aligned with respect to each other.

In a short-period fiber Bragg grating, the spacing between the grating elements **112** which is typically in the range 0.1 to 15 microns is chosen to shift the transmitted light in the region of the selected wavelength, λ_p , from the forward core-guided mode **114** into a backward core-guided or backward cladding mode. Thereby, reducing the intensity of the light, centered about λ_p , transmitted through the core **106**.

In an LPFG, the spacing between the grating elements **112** which is typically in the range 15 to 1,500 microns is chosen to shift the transmitted light in the region of the selected wavelength, λ_p , from the forward core-guided mode **114** into a forward cladding mode. Thereby, reducing the intensity of the light, centered about λ_p , transmitted through the core **106**.

In the preferred embodiment, the fiber grating **104** is a LPFG having grating elements **112** that are separated with a periodicity of Λ and a width, W , that is typically in the range of $(1/10)\Lambda < W < (9/10)\Lambda$. The width of the perturbation in the refractive index defines the width, W , of the grating element **112**. Generally, the perturbation in the refractive index varies smoothly across the width of the grating element and the variation can be represented as a Gaussian shape or other shape. It should be noted that the periodicity and the width are design parameters, and those skilled in the art will recognize the periodicity, Λ and/or width, W , can be adjusted to fit design considerations.

Refer now to FIG. 3, which shows a cross-sectional view of an exemplary grating element **112**, the core **106** is generally cylindrical and centered around the centerline **110** (not shown) and has a radius of R_1 , and the cladding **108** is generally annular with an inner radius of R_1 and an outer radius of R_2 . In the preferred embodiment the grating element **112** is azimuthally varying about the centerline **110**. The grating element **112** includes a perturbation **118**, which includes cladding perturbation **120** and core perturbation **122** and an unperturbed region **124**. The index of refraction at a point, given in polar coordinates (r, ϕ) in the grating element **112** can be given by the following equation:

$$n(r, \phi) = \begin{cases} n_{core}(r, \phi), & 0 < r \leq R_1, \alpha < \phi \leq 2\pi - \alpha \\ n_{core}(r, \phi) + \Phi_1(r, \phi), & 0 < r \leq R_1, -\alpha < \phi \leq \alpha \\ n_{cladding}(r, \phi), & R_1 < r \leq R_2, \alpha < \phi \leq 2\pi - \alpha \\ n_{cladding}(r, \phi) + \Phi_2(r, \phi), & R_1 < r \leq R_2, -\alpha < \phi \leq \alpha \end{cases}$$

in the grating element **112** can be given by where the perturbation in the core and the cladding is given by ϕ_1 and ϕ_2 , respectively. The quantities ϕ_1 and ϕ_2 can be restricted to refractive index perturbations (phase change) or can be restricted to optical absorption perturbations. In the latter case, ϕ_1 and ϕ_2 represent perturbations in the imaginary part of the refractive index. In the general case, ϕ_1 and ϕ_2 can represent perturbations in both the real and imaginary parts of the refractive index. It should be noted that the perturbation in the core **106** may be different from, or the same as, the perturbation in the cladding **108**.

In the simplest case, the index of refraction of the grating element **112** is given by the following equation:

$$n(r, \phi) = \begin{cases} n_{core}, & 0 < r \leq R_1, \alpha < \phi \leq 2\pi - \alpha \\ n_{core} + \Phi_1, & 0 < r \leq R_1, -\alpha < \phi \leq \alpha \\ n_{cladding}, & R_1 < r \leq R_2, \alpha < \phi \leq 2\pi - \alpha \\ n_{cladding} + \Phi_2, & R_1 < r \leq R_2, -\alpha < \phi \leq \alpha \end{cases}$$

where the core **106** and the cladding each have uniform index of refraction, and the perturbations in the core **106**, ϕ_1 , and the cladding **108**, ϕ_2 , are also uniform. However, even in the simplest case, the index of refraction varies as the azimuthal angle crosses the boundary between the perturbation region **118** and the unperturbed region **124**.

It should be noted that FIG. 3 is only an exemplary illustration of an embodiment of the invention. Other, non-limiting examples of grating elements having azimuthal asymmetry are illustrated in FIGS. 4A–4O. Briefly described, the grating elements **312(A)**, shown in FIG. 4A, includes a perturbation **318(A)** that extends generally inward from the outer surface **302** into the cladding **308**. The perturbation **318(A)** is relatively small, extending only a portion of the way from the outer surface **302** towards the core **306**, and is generally a pie shaped wedge having a generally acute angle at its vertex **314(A)**.

The grating element **312(B)**, shown in FIG. 4B, includes a perturbation **318(B)** extending generally inward from the outer surface **302** into the core **306**. The perturbation **318** is approximately pie shaped with an acute angle at its vertex **314(B)**.

The grating element **312(C)**, shown in FIG. 4C, includes a perturbation **318(C)** extending generally inward from the outer surface **302** beyond the core **306** into the distal region of the cladding **308**. The perturbation **318(C)** is approximately pie shaped with an acute angle at its vertex **314(C)**.

The grating element **312(D)**, shown in FIG. 4D, includes a perturbation **318(D)** that extends generally inward from the outer surface **302** into the cladding **308**. The perturbation **318(D)** extends from the outer surface **302** towards the core **306** and defines an acute angle, which is in the approximate range of 30 to 90 degrees at its vertex **314(D)**.

The grating element **312(E)**, shown in FIG. 4E, includes a perturbation **318(E)** that extends generally inward from the outer surface **302** into the core **306**. The vertex **314(E)** of the perturbation **318(E)** has an acute angle, which is in the approximate range of 30 to 90 degrees.

The grating element **312(F)**, shown in FIG. 4F, includes a perturbation **318(F)** that extends generally inward from the outer surface **302** beyond the core **306** into the distal region of the cladding **308**. The vertex **314(F)** of the perturbation **318(F)** defines an acute angle, which is in the approximate range of 30 to 90 degrees.

The grating element **312(G)**, shown in FIG. 4G, includes a perturbation **318(G)** that extends generally inward from the outer surface **302** and to the cladding **308**. An arc **316(A)**, the center of which is not shown and which is outside of the grating element **312(G)**, defines the perturbation **318(G)**.

The grating element **312(H)**, shown in FIG. 4H, includes a perturbation **318(H)** that extends generally inward from the outer surface **302** into the core **306**. An arc **316(B)**, the center of which is not shown and which is outside of the grating element **312(H)**, defines the perturbation **318(H)**.

The grating element **312(I)**, shown in FIG. 4I, includes a perturbation **318(I)** that extends generally inward from the outer surface **302** past the core **306** and into the distal region

of cladding 308. An arc 316(C), the center of which is not shown and which is outside of the grating element 312(I), defines the perturbation 318(I).

The grating element 312(J), shown in FIG. 4J, includes at least one perturbation 318(J). The perturbation 318(J) can be of any arbitrary shape and size and can be located anywhere in the grating element 312(J), provided the azimuthal symmetry about the center of the core is broken. It should be noted that if the perturbation 318(J) extends across the entire grating element 312(J), then the perturbation 318(J) has azimuthal asymmetry, otherwise, the perturbation could be uniform. In the preferred embodiment, the perturbation 318(J) has azimuthal asymmetry about the center of the core 306.

The grating elements 312(K), shown in FIG. 4K, includes a pair of generally pie shaped perturbations 318(K) extending generally inward from the outer surface 302 into the core 306. The perturbations 318(K) are approximately linearly aligned.

The grating element 312(L), shown in FIG. 4L, includes three generally pie shaped perturbations 318(L), each perturbation 318(L) extends generally inward from the outer surface 302 into the core 306. The perturbations 318(L) are approximately equally spaced from each other.

The grating element 312(M), shown in FIG. 4M, includes four approximately pie shaped perturbations 318(M) each of which extends generally inward from the outer surface 302 into the core 306. The perturbations 318(M) are approximately equally spaced from each other.

The grating element 312(N), shown in FIG. 4N, includes five approximately pie shaped perturbations 318(N), each of which extends generally inward from the outer surface 302 into the core 306. The perturbations 318(N) are approximately equally spaced from each other.

The grating element 312(O), shown in FIG. 4O, includes four approximately pie shaped perturbations 318(O), each of which extends generally inward from the outer surface 302 into the core 306. In contrast to FIGS. 4K through 4N, the perturbations 318(O) are not approximately equally spaced from each other.

It should be noted that the grating elements 312 are non-limiting examples of embodiments of the grating elements having azimuthal asymmetry. All grating elements having azimuthal asymmetry are intended to be within the scope of the invention.

Referring now to FIG. 5, an optical fiber 400 having a fiber grating 404, which includes a plurality of azimuthally varying grating elements 412, is configured such that the centerline 410 is curved. In this example, the optical fiber 400 is bent into an arc having an arbitrary radius of curvature. Generally, the optical characteristics, such as the coupling between core mode 414 which propagates into the fiber core and cladding mode 416, of the fiber grating 404 are a function of the alignment of the azimuthally varying grating elements 412. The coupling between the core mode 414 and the cladding mode 416 can be tuned by changing the relative orientation of the azimuthally varying grating elements 412. It will be demonstrated hereinbelow that with appropriately bending of the fiber grating 404 the coupling between the core modes 414 and the cladding modes 416 can be tuned at desired frequencies.

Although FIG. 5 illustrates changing the optical path by smoothly bending the optical fiber, any method of changing the relative orientations of the grating elements including but not limited to, kinking, micro-bending, are intended to be included within the scope of the invention. Furthermore, when the optical fiber grating 404 is axially twisted about

centerline 410, the relative orientations of the perturbations in the grating elements 412 are changed. Consequently, the fiber grating 404 can be tuned to couple to desired frequencies with appropriate twisting of the fiber grating 404. The coupling between modes can also be tuned by a combination of rotation of the optical fiber 400 and deformation of the fiber grating 404.

Referring to FIG. 6, in one embodiment, an azimuthally varying grating element 112 is produced by illuminating a portion of an optical fiber 100 by a laser beam. To make the grating element 112, incident light 502 of intensity 10 is transversely applied to a region of the optical fiber 100. The wavelength of the incident light is chosen such that it is highly absorbed by optical fiber 100, thereby heating the region of the optical fiber 100 that absorbs the incident light 502. An amplitude mask can be used with one slit or multiple slits to control the light pattern impinging on the fiber.

FIG. 6 also represents simulated results of normalized incident light intensity in optical fiber 100. In this experiment optical fiber 100 is a standard telecommunications matched-clad glass fiber and the incident light is a laser beam from a CO2 laser. Details of this simulation can be found in "Axial Rotation Dependence of Resonances in Curved CO2-Laser-Induced Long-Period Fibre Gratings," Electronic Letters, vol. 36, pp. 1354-1355, Aug. 3, 2000, which is hereby incorporated by reference.

For the purposes of this disclosure, we shall define a top surface region 504 as being the portion of the grating element 112 in which the normalized intensity is approximately between 0.2 and 1, and we shall define a bottom surface region 506 as being the portion of the grating element 112 that is radially distal from the top surface region 504. Clearly, almost all of the incident light is absorbed by the optical fiber 100 within approximately 20 microns from the incident surface. The incident light 502 is used for creating a temperature gradient between the upper surface 504 and the bottom surface 506.

A perturbation in the refractive index of the optical fiber 100 is produced in the portion of the optical fiber 100 that is heated by the incident light 502. Generally, the magnitude of the perturbation in the refractive index is related to the temperature of the heated portion. Thus, the incident light 502 produces a grating element 112 having a given perturbation in the refractive index in the upper surface region 504 and a smaller perturbation in the bottom surface region 506. Likewise, the perturbation in the refractive index of the core 106 is generally greatest in the region of the core proximal to the top surface region 504 and least in the region distal from the top surface region 504. It is also understood that the magnitude of the refractive-index perturbation can be controlled by the laser beam intensity.

While the top surface region 504 absorbs more energy than does the bottom surface region, the absorption is generally symmetric about a vertical line (not shown) at $x=0$. Thus, when the optical fiber 100 is initially symmetric about a vertical line at $x=0$, the perturbation in the refractive index caused by heating from incident laser light 502 is also symmetric about a vertical line at $x=0$, and consequently, the optical characteristics of the grating element 112 are symmetric about a vertical line at $x=0$.

In the preferred embodiment, a first grating element 112 of the fiber grating 104 is produced by applying the incident light 502 to a portion of the optical fiber for a predetermined duration and at a predetermined intensity. A subsequent grating element, which is a predetermined distance from the first grating element, is produced by applying the incident light 502 for a predetermined duration and intensity to a

11

subsequent portion of the optical fiber **100**. In the preferred embodiment, the optical fiber **100** is positioned in a given orientation relative to the incident laser beam and the relative orientation of the top surface region **504** for each subsequent grating element **112** is predetermined.

Although, the preferred embodiment uses a CO₂ laser as a heat source to produce the azimuthally varying grating elements **112** in the optical fiber **100**, other embodiments include but are not limited to heat sources such as plasma arcs, ultraviolet lasers, visible lasers, narrow flames, etc.

In another embodiment, azimuthally varying grating elements are produced by including dopants, such as, but not limited to, germanium, boron, and hydrogen in optical fiber **100** and exposing the dopants to light sources, such as an UV laser. In this embodiment, during the fabrication of the optical fiber **100**, the dopants are disposed in the optical fiber according to a predetermined or a random azimuthally varying pattern, non-limiting examples of which are shown in FIGS. 4A-4O. It is to be understood that a plurality of dopants can be disposed in a azimuthally varying grating element. In one embodiment, a first region has a first dopant disposed therein and a second region has a second dopant disposed therein. In another embodiment, a plurality of dopants are disposed in a region of the azimuthally varying grating element. In yet another embodiment, a dopant or a plurality of dopants are disposed in one or several regions of the azimuthally varying grating element and the concentration of the dopant or dopants is varied.

Typically, the grating elements **112** are configured such that each top surface region **504** is approximately linearly aligned. In alternative embodiments, the top surface regions **504** of the grating elements **112** are aligned according to a predetermined scheme. Non-limiting examples of two alignment schemes are shown in FIGS. 7A and 7B. In FIG. 7A, fiber grating **104** includes a plurality of grating elements **112(A)**-**112(F)**. In this exemplary fiber grating **104**, the grating elements **112** are rotationally aligned such that each grating element is offset by a predetermined amount. For example, grating element **112(B)** is azimuthally rotated about the centerline (not shown) by 30 degrees relative to the orientation of the grating element **112(A)**. In this example, except for being rotated with respect to each other, the grating elements are essentially the same. All of the perturbations **118** were produced by absorbing essentially the same amount of energy, with each incident top surface region being rotationally offset. Thus, equivalent portions of the grating elements are rotationally offset. For example, region **120** of the perturbation **118** is essentially the same in each grating element **112**. It should be clear that the amount of rotation of each grating element **112** is a design choice, and that each grating element **112** need not be rotated by a multiple of a predetermined amount. For example, the grating element **112(B)** could be rotated by 11 degrees and the grating element **112(C)** could be rotated by 60 degrees relative to grating element **112(A)**.

In FIG. 7B, the grating elements **112** of exemplary fiber grating **104** are periodically rotationally offset. In this example, grating elements **112(B)**, **112(D)** and **112(F)** are rotationally offset by 90 degrees with respect to grating elements **112(A)**, **112(C)** and **112(E)**. It should be clear that the amount of rotation is a design choice, as is the periodicity of the rotated gratings. For example, in another embodiment, the grating elements could be grouped into three sets, each of the three sets having different rotational orientation.

Referring now to FIGS. 8-12, shown are transmission characteristics of two exemplary LPFG (LPFG). The two exemplary LPFG's were fabricated period by period using

12

carbon dioxide laser pulses. Gratings were written into standard matched-clad single-mode fiber (Corning SMF 28) with no hydrogen loading or special treatment of any kind. The experimental configuration, details of which can be found in "Tuning, Attenuating, and Switching by Controlled Flexure of Long-Period Fiber Gratings," Optics Letters, vol. 25, pp. 61-63, Jan. 15, 2001, which is incorporated herein by reference, included a computer-controlled translation stage that positioned the fibers so that single pulses of CO₂ laser light of 10.6 μ m wavelengths could be focused onto the fiber at desired positions along the fiber axis. The grating period, Λ , was 480 μ m. For LPFG No. 1, the number of periods, N, was 40 and the incident writing energy was 88 mJ/period (0.40 watts for 0.22 seconds). For LPFG No. 2, the number of periods, N, was 50 and the incident writing energy was 100 mJ/period (0.40 watts for 0.25 seconds). The transmission spectra of these LPFG's were measured from 1000 nm to 1600 nm using an optical spectrum analyzer (Hewlett Packard Model 70951B). For the measurements presented herein the fibers containing the LPFG's were placed on top of a horizontal plastic optical fiber platform and held there under slight tension (a tensile force of 25 milli-Newtons). Beneath the horizontal plastic optical fiber platform, at approximately the center, a micropositioner was used to deflect upwardly the plastic optical fiber platform and the LPFG's, which were correspondingly flexed as shown in FIG. 4. The radius of curvature could be varied from $R=\infty$ to 0.2 meters (curvature varied from $C=1/R=0$ m⁻¹ to 5 m⁻¹).

Referring now to FIG. 8, shown is the transmission characteristic for the long period optical fiber grating number 1 having 40 grating elements **112** with a periodicity of 480 μ m. FIG. 8 demonstrates the strong dependence of the transmission on the axial rotational orientation of the optical fiber **100**, where ϕ' denotes the azimuthal rotation of the optical fiber from the configuration illustrated in FIGS. 7A-7B. The grating elements had the same general azimuthal symmetry as the grating element shown in FIG. 6. From symmetry arguments, the transmission at $\phi'=90^\circ$ and $\phi'=270^\circ$ should be the same and this was observed experimentally to a close approximation. The diffraction of the core modes **114** into the cladding modes **116** as illustrated by transmission magnitude, τ , is sensitive to the axial rotational orientation of the fiber.

The strong axial rotation orientation dependence observed in CO₂ laser induced LPFG's provides an important additional degree of freedom for tailoring the transmission characteristics of wavelength tuners, attenuators, switches, and modulators. This degree of freedom is not present in symmetric gratings, such as conventional UV induced grating. By proper choice of axial rotation angle ϕ , desired characteristics such as wavelength tuning at constant attenuation and variable attenuation at constant wavelength can be achieved.

Referring now to FIGS. 9-12, six to ten distinct resonances were typically observed in the wavelength range from 1,000 to 1,600 nanometers. Varying the curvature, C, of the LPFG's caused the resonance to change both in attenuation and in wavelength. Also, the resonance changed significantly with axial rotation of the fiber. Consequently, the evolution of the resonance with increasing curvature depends sensitively on the axial orientation of the LPFG with respect to the plane of curvature. Orienting LPFG No. 1 appropriately on the flexing optical fiber platform enabled wavelength tuning at a constant attenuation as shown in FIG. 9. In this particular case, an attenuation of 21 dB was tuned over a wavelength range of 20 nanometers from 1,472

13

nanometers to 1,452 nanometers by changing the curvature of the LPFG No. 1 from C1=2.23 m⁻¹ to C6=3.85 m⁻¹, thereby demonstrating constant attenuation tuning with an LPFG. The radius of curvature for each of the labeled curves shown in FIGS. 9 and 10, are given in Table 1.

TABLE 1

Bending curvatures for optical characteristics shown in FIGS. 9 and 10.					
C1	C2	C3	C4	C5	C6
2.23 m ⁻¹	2.61 m ⁻¹	2.98 m ⁻¹	3.23 m ⁻¹	3.48 m ⁻¹	3.85 m ⁻¹

The six transmission spectra shown in FIG. 9 are representative of the spectra for the 30 curvatures applied. The tuning of the center wavelength with curvature is shown in FIG. 10. A total of 38 spectra are summarized in FIG. 10. The wavelength tuning is linear with curvature and has a tuning sensitivity of 11.92 nanometers/m⁻¹ over most of the range. It should be noted that the transmission increases (attenuation decreases) at the high and low curvature ends for the 30 curvatures shown in FIG. 10.

Referring now to FIG. 11, shown are the transmission characteristics of an exemplary LPFG 2. The transmission characteristics demonstrate variable attenuation/switching/modulation at a constant wavelength by appropriate axial rotation of the LPFG No. 2 coupled with bending the LPFG No. 2. In this case, the attenuation at a wavelength of 1,422 nanometers was varied over a 19 dB range by changing the curvature of the LPFG No. 2 from C1=0.0 m⁻¹ to C9=1.61 m⁻¹. The radius of curvatures for C1 through C9, shown in FIGS. 11 and 12, are given in Table 2. The nine transmission spectra shown in FIG. 10 are representative of the spectra for 21 curvatures (a total of 22 spectra) applied in this experiment. The transmission (attenuation) as a function of curvature is shown in FIG. 11. As curvature was increased beyond C9=1.61 m⁻¹ (overall minimum transmission) the transmission increased (attenuation decreased) as shown in FIG. 12. For axial orientations other than those used in FIGS. 9–12, both the wavelength and the transmission simultaneously change when the LPFG region was flexed. A wide variety of wavelength transmission characteristics were observed.

TABLE 2

Bending curvatures for optical characteristics shown in FIGS. 11 and 12.								
C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉
0.0 m ⁻¹	0.25 m ⁻¹	0.73 m ⁻¹	0.98 m ⁻¹	1.17 m ⁻¹	1.29 m ⁻¹	1.42 m ⁻¹	1.48 m ⁻¹	1.61 m ⁻¹

As wavelength tuners (FIG. 9) and as variable attenuators/switches/modulators (FIG. 11), these grating devices have significant potential for application to fiber optic network telecommunications. A major advantage is that the modulating device is contained within the fiber as opposed to being external to the fiber. Piezoelectric, electromechanical or similar transducers, including but not limited to a micro-electronic apparatus, mechanical-apparatus, an electromechanical solenoid, a linear motor, a stepping motor and mechanical cam, a hydraulic apparatus, a pneumatic apparatus, a thermomechanical apparatus, a photoelastic apparatus, an acoustic apparatus, a magnetostrictive apparatus, an electrostrictive apparatus, and a piezo-electric ceramic platform can be attached to the fiber to make the tuning,

14

attenuation, switching, and modulation electrically controllable by controlling the positioning of the fiber. The wavelength tuning and variable attenuation effects can be applied in sensor applications, and other applications.

Referring now to FIG. 13, shown is a relative index difference profile for the cladding region of a hydrogen-loaded optical fiber that has had a plurality of grating elements with periodicity of 480 μm written into the optical fiber by a CO₂ laser. The horizontal axis is the axial direction of the optical fiber, and the vertical axis is the relative index difference, which is given by

$$\Delta = [n(r,z) - n_0] / n_0,$$

where n₀ is the index of refraction of an index matching oil chosen to match the index of refraction of the unperturbed cladding region and where n(r,z) is the index of refraction of the radial region measured from the centerline at positions along the centerline. Using transverse interferometry, the relative index difference was measured on the side of the optical fiber upon which the laser beam was incident. The peaks in the relative index difference, which are about 0.05%, correspond to the grating elements and have the appropriate periodicity. The value of n₀ was 1.458, so the increase in the refractive index of the cladding region upon which the laser beam was incident upon was about 1.5×10⁻³.

Although the experimental results given hereinabove were for LPFGs, it is to be understood that they were exemplary fiber grating, which were not intended to limit the scope of the invention. Other fiber gratings included in the scope of the invention include, but are not limited to, short-period fiber Bragg gratings. Other exemplary fiber gratings are shown in FIGS. 14A–14F.

Optical fiber grating 1300(A), shown in FIG. 14A, has a fiber grating 1304 disposed therein. The fiber grating 1304 includes a plurality of approximately equally spaced grating elements 1312 extending from the cladding into the core.

Optical fiber grating 1300(B), shown in FIG. 14B, has a pair of fiber gratings 1304(A) and 1304(B) disposed therein. Each fiber grating 1304 includes a plurality of approximately equally spaced grating elements 1312 extending from the cladding into the core. The periodicity of the grating elements 1312 included in the fiber grating element 1304(A) is approximately the same as the periodicity of the grating elements 1312 in the fiber grating 1304(B).

Optical fiber grating 1300(C), shown in FIG. 14C, has a pair of fiber gratings 1304(c) and 1304(D) disposed therein. Each fiber grating 1304 includes a plurality of approximately equally spaced grating elements 1312 extending from the cladding into the core. The periodicity of the grating elements 1312 included in the fiber grating element 1304(D) is approximately greater than the periodicity of the grating elements 1312 in the fiber grating 1304(C). The difference in the periodicity is a design choice, as is the relative positions of fiber gratings 1304(C) and 1304(D).

Optical fiber grating 1300(D), shown in FIG. 14D, has a chirped fiber grating 1304 disposed therein, which includes a plurality of grating elements 1312 having non-uniform longitudinal spacing extending from the cladding into the core. The spacing between grating elements 1312 in fiber grating 1304 of optical fiber 1310(D) is a design choice. In an alternative embodiment, the spacing between grating elements can conform to any predetermined or random pattern.

Optical fiber grating 1300(E), shown in FIG. 14E, has a pair of chirped fiber gratings 1304(E) and 1304(F) disposed

15

therein. Each fiber grating **1304(E)** and **1304(F)** includes a plurality of grating elements **1312** extending from the cladding into the core. The spacing of the grating elements **1312** included in the chirped fiber grating element **1304(E)** is approximately the same as the spacing of the grating elements **1312** included in the chirped fiber grating **1304(F)**, and the spacing generally decreases from left to right in both of the fiber gratings, **1304(E)** and **1304(F)**.

Optical fiber grating **1300(F)**, shown in FIG. **14F**, has a pair of chirped fiber gratings **1304(G)** and **1304(H)** disposed therein. Each fiber grating **1304(G)** and **1304(H)** includes a plurality of grating elements **1312** extending from the cladding into the core. The spacing of the grating elements **1312** included in the chirped fiber grating element **1304(G)** is approximately the same as the spacing of the grating elements **1312** included in the chirped fiber grating **1304(H)**. However, the spacing of the grating elements included in the chirped fiber grating **1304(G)** decreases from left to right and the spacing of the grating elements **1312** included in the chirped fiber grating **1310(H)** increases from left to right.

The embodiments shown in FIGS. **14A–14F** are non-limiting examples of possible configurations of azimuthally varying grating elements. Other non-limiting configurations include, but are not limited to, disposing the azimuthally grating elements **1312** in a portion of the core or in a portion of the cladding or across the core and cladding.

Referring now to FIGS. **15A–15E**, FIG. **15A** is a side view of tuning/attenuating/switching/modulating fiber grating device **1400**, hereinafter collectively referred to as “tuning device.” Tuning device **1400** includes a housing **1402** having opposed ends **1404** that are adapted to be coupled to devices and/or fibers within an optical network. Extending between the opposed ends **1404** are opposed sidewalls **1406** that have bottom wall **1408** and top wall **1410** extending there between. Housing **1402** has a generally hollow interior extending between the opposed ends **1404**.

Tuning device **1400** further includes, disposed within the generally hollow interior of the housing **1402**, a tuning actuator **1412**, a plurality of posts **1414**, an optical fiber platform **1416** and an optical fiber **100** having opposed ends **102**. The opposed ends **1404** of housing **1402** include aligned openings **1418** for receiving the opposed optical fiber ends **102**. In the preferred embodiment, the openings are vertically aligned approximately half way between the bottom wall **1408** and the top wall **1410**, and extending between the openings **1418** is optical fiber **100**, which includes a plurality of azimuthally varying grating elements in the grating element **104**. The openings **1418** are typically contained within standard commercial fiber optic connectors.

Referring now to FIG. **15B**, shown is a cutaway perspective view of tuning device **1400**, as seen when viewed along line I—I of FIG. **15A**. Fixedly attached to the bottom wall **1408**, approximately half way between opposed ends **1404** and extending at least partially between opposed sidewalls **1406**, is tuning actuator **1412**. Disposed on tuning actuator **1412** is optical fiber platform **1416**, which in the preferred embodiment is generally a rectangular sheet of resilient material such as plastic or metal defined by opposed ends **1420** and opposed sides **1422**, for positioning the optical fiber. The optical fiber platform **1416** further includes a bottom surface **1424**, which engages tuning actuator **1412**, and a generally flat top surface **1426** that has a generally V-shaped groove **1428** formed therein. The V-shaped groove **1428** extends between opposed platform ends **1420** and is aligned with optical fiber **100**, which is disposed therein. In

16

the preferred embodiment, each of the posts includes a generally V-shaped groove **1430** for receiving a portion of the optical fiber **100**. The generally V-shaped grooves formed in the posts **1414** are aligned with the platform V-shaped groove **1428**, straddling the optical fiber **100**, and the optical fiber **100** is affixed to the optical fiber platform **1416**, proximal to opposed platform ends **1420**, by means such as adhesive. In an alternative embodiment, the optical fiber **100** is disposed directly on the tuning actuator **1412**, thus the tuning actuator can also be used for positioning the optical fiber **100** in a given orientation between opposed ends **1404** of housing **1402** and for flexing or bending the optical fiber **100**.

Rigidly affixed to sidewalls **1406** and extending therein, are the plurality of posts **1414** made from a rigid material such as metal or hard plastic. The posts are vertically aligned such that the posts engage the top surface **1426** of the optical fiber platform **1416** proximal to the opposed platform ends **1420**.

Referring now to FIGS. **15A** and **15C**, the optical fiber **100** is disposed in the groove of the optical fiber platform **1416** and fixedly attached thereto, such that the grating region **104** extends at least partially between the posts **1414**. In FIG. **15A**, tuning actuator **1412** is shown coupled to the bottom wall **1408** of housing **1402** in a first configuration engaging the bottom surface **1424** of optical fiber platform **1416**.

The tuning actuator **1412**, the posts **1414**, the optical fiber platform **1416** and the housing **1402** cooperate to deform optical fiber **100**. The tuning actuator **1412**, which is rigidly coupled to bottom wall **1408** and in contact with optical fiber platform **1416**, is adapted to vertically extend and contract. Referring now to FIG. **15C**, shown is tuning actuator **1412** in a second configuration in which the tuning actuator **1412** is partially extended upwards, thereby pressing optical fiber platform **1416** upwards. The plurality of posts **1414** engage the top surface **1426** of the optical fiber platform **1416** proximal to opposed platform ends **1420**, thereby preventing the end portions of the optical fiber platform from being vertically raised by the extension of actuator **1412**. In response to the extension of actuator **1412** the portion of the optical fiber platform extending between the posts **1414(A)** and **1414(B)** becomes curved, as shown in FIG. **15B**. When the actuator **1412** is contracted to its first configuration, shown in FIG. **15A**, the optical fiber platform, which is made from a resilient material, returns to its generally flat shape.

In the preferred embodiment, the optical fiber **100** is disposed in groove **1428** and fixedly attached thereto by means such as adhesive. The optical fiber **100** is positioned such that at least a portion of the grating region **104** of the optical fiber is disposed between posts **1414(A)** and **1414(B)**. Thus, when the tuning actuator **1412** is extended or contracted, thereby changing the curvature of the optical fiber platform **1416**, the curvature of the grating region of the optical fiber changes correspondingly. The optical fiber platform **1416**, with the optical fiber disposed thereon, can be bent or flexed by a variety of devices such as, but are not limited to, a piezoelectric apparatus, a micro-electro-mechanical apparatus, an electromechanical solenoid, a linear motor, a stepping motor and mechanical cam, a hydraulic apparatus, a pneumatic apparatus, a thermomechanical apparatus, a photoelastic apparatus, an acoustic apparatus, a magnetostrictive apparatus, and an electrostrictive apparatus.

In an alternative, non-limiting, embodiment, optical fiber **100** is fixedly clamped to optical fiber platform **1416** such that changes in the curvature of the optical fiber **100** correspond to changes in the contraction/expansion of the tuning

17

actuator. In yet another non-limiting embodiment, optical fiber 100 is coupled to opposed ends 1404 such that the optical fiber extending therebetween engages the optical fiber platform, and such that changes in the curvature of the optical fiber correspond to changes in the expansion/contraction of tuning actuator 1412.

In another non-limiting embodiment, the opposed optical fiber ends 102 of the optical fiber 100 are rotatably mounted to opposed ends 1404 of tuning device 1400. Each opposed optical fiber end 102 of optical fiber 100 is independently axially rotatable. In this embodiment, the optical fiber, extending between the opposed ends 1404 of the tuning device, is not adhered to the optical fiber platform 1416. Rather, the optical fiber 100 is disposed in the platform groove 1428 and is rotatable therein. Thus, the grating region 104 of the optical fiber 100 is rotated by rotating the optical fiber ends 102. The grating region 104 can also be axially twisted about the centerline by counter rotating the opposed optical fiber ends 102, or by rotating just one of the opposed optical fiber ends, or by rotating one of the optical fiber ends. It should be noted that the optical fiber 100 is axially rotatable/twistable even when the optical fiber is not linearly aligned between the opposed ends 1404, e.g., even when the optical fiber region is curved in response to curvature of optical fiber platform 1416.

FIGS. 15D and 15E show an alternative embodiment of the tuning device 1400. In this embodiment, the optical fiber 100 is disposed on an optical fiber platform 1430 that is a commercially available piezo-ceramic layer, which are known to those skilled in the art. The piezo-ceramic layer includes opposed electrodes 1432 disposed on intermediate layers 1434, which sandwich a piezo-ceramic layer 1436 such as barium titanate or lead lanthanum zirconate titanate. The optical fiber platform 1430 curves in response to a voltage applied to the opposed electrodes 1432, as illustrated in FIG. 15E, thereby inducing a change in curvature of the optical fiber 100 disposed thereon. Thus, optical fiber platform 1430 positions the optical fiber 100 extending between opposed ends 1404 of housing 1402 and flexes to change the curvature of the grating region 104 of optical fiber 100 disposed thereon.

As previously demonstrated hereinabove, small changes in the curvature of the grating region may produce dramatic changes in the optical transmission characteristics of the optical fiber. Those skilled in the art will recognize that other embodiments, different than those disclosed hereinabove, exist for changing the relative orientation of the grating region, and all such embodiments are intended to be within the scope of the invention. The above-cited embodiments are intended to be non-limiting examples for positioning and flexing the optical fiber having azimuthally varying grating elements disposed therein.

From the above discussion of the current invention it should be understood by those skilled in the art that many implementations of the current invention are possible. It should be emphasized that the above-described embodiments of the present invention, particularly, any "preferred" embodiments, are merely possible examples of implementations, merely set forth for a clear understanding of the principles of the invention. Many variations and modifications may be made to the above-described embodiment(s) of the invention without departing substantially from the spirit and principles of the invention. All such modifications and variations are intended to be included herein within the scope of this disclosure and the present invention and protected by the following claims.

18

The invention claimed is:

1. A method of making a fiber grating in an optical fiber, the method comprising the steps of:

disposing a length of optical fiber in a predetermined position, the length of optical fiber defining a centerline and having a core and a cladding disposed on said core, the optical fiber having predetermined optical characteristics; and

heating at least a portion of said optical fiber with a heat source, wherein heat from said heat source produces a perturbation in the refractive index of the optical fiber, and the refractive index of the optical fiber varies azimuthally about the centerline in the perturbation.

2. The method of claim 1, wherein said perturbation extends from said cladding into said core of the optical fiber.

3. The method of claim 1, wherein a plurality of portions of said optical fiber are heated, each heated portion separated by a predetermined distance measured along said centerline of said optical fiber.

4. The method of claim 3, wherein said heat source is an electric arc.

5. The method of claim 3, wherein said heat source is a laser.

6. The method of claim 5, wherein a single-slit mask is used to control the width of the laser beam.

7. The method of claim 5, wherein a multiple-slit mask is used to control the beam profile.

8. The method of claim 5, wherein said heat source is a CO₂ laser.

9. A method for making a fiber grating in an optical fiber, the method comprising the steps of:

disposing a dopant in a non-uniform generally planar pattern in an optical fiber, the optical fiber defining a centerline;

irradiating the dopants with a laser beam, wherein the irradiated dopant produce an azimuthally varying perturbation in the refractive index of the optical fiber about the centerline of the optical fiber in the plane of the dopant.

10. The method of claim 9, wherein the optical fiber includes a core and a cladding, and the dopant is disposed in at least a portion of the cladding.

11. The method of claim 9, wherein the optical fiber includes a core and a cladding, and the dopant is disposed in at least a portion of the core.

12. The method of claim 9, wherein the optical fiber includes a core and a cladding, and the dopant is disposed in at least a portion of the core and at least a portion of the cladding.

13. The method of claim 9, wherein the concentration of the dopant varies.

14. The method of claim 9, wherein the pattern for disposing the dopant includes a first region and a second region, each region having the dopant disposed therein.

15. The method of claim 14, wherein the first and second region are non-contiguous.

16. The method of claim 9, further including the step of: prior to the step of irradiating, disposing a second dopant in a second generally planar non-uniform pattern.

17. The method of claim 16, wherein the first and second dopants are disposed in approximately the same plane.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 7,085,451 B2
APPLICATION NO. : 11/220337
DATED : August 1, 2006
INVENTOR(S) : Gaylord et al.

Page 1 of 2

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 2, line 64, after the words “the exterior” insert the word --of--.

Column 3, line 67, after the words “of optical” insert --fiber--.

Column 4, line 25, after the words “the optical” insert --fiber--.

Column 7, line 11, delete “.” and replace with --, thereby--.

Column 7, line 18, delete “.” and replace with --, thereby--.

Column 7, line 21, delete the “a” and replace with --an--.

Column 7, line 34 delete the word “Refer” and replace with --Referring--.

Column 8, line 29, delete “318” and replace with --318(B)--.

Column 9, line 59, delete “appropriately” and replace with --appropriate--.

Column 11, line 6, after the word “although,” delete the “;”.

Column 11, line 20, delete the word “a” and replace with --an--.

Column 11, line 66, delete “LPFG (LPFG)” and replace with --LPFGs--.

Column 13, line 42, delete “change” and replace with --changed--.

Column 14, line 30, delete “grating” and replace with --gratings--.

Column 14, line 48, delete “1304(c)” and replace with --1304(C)--.

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Page 2 of 2

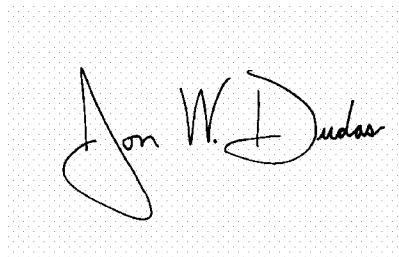
It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 16, line 57, delete "are".

Column 16, line 64, delete "non-limiting, embodiment" and replace with --non-limiting embodiment--.

Signed and Sealed this

Twenty-sixth Day of December, 2006

A handwritten signature in black ink, reading "Jon W. Dudas". The signature is written in a cursive style with a large, stylized "J" and "D".

JON W. DUDAS
Director of the United States Patent and Trademark Office